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Sun tracker systems effects on flat plate photovoltaic PV systems performance for different sky states: A case of an arid and hot climate.

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Abstract

This work aims at determining the most appropriate sun tracking system. The effect of using different types of sun tracking systems on the flat plate photovoltaic system performance for different sky states has been investigated. Several days representing different seasons have been considered. The corresponding main parameters affecting the amount of the electrical energy output and the gains have then been compared to those experienced with two traditional fixed photovoltaic systems inclined according to a yearly and a seasonal optimum slope. Additionally, five configurations of sun tracking systems have been considered while a seasonal and a yearly optimum slope have been applied to those based on rotating axes systems. Hourly data collected over thirty one days for different seasonal sky conditions have been employed. The daily collected global solar radiation and produced electrical energy as well as the electrical gains related to the different moving panels have been quantified separately for each sky state. It is found that for a completely clear day, the highest obtained gains are those related to the two-axis sun tracker systems while the day length is the main parameter affecting these gains. On the other hand, for the partially clear days, the gain amounts mainly depend on the daily clarity level factors and on the seasonal variation of day length values. For a cloudy day, however, all considered systems produced the same electrical energy. Furthermore, the horizontal position of the photovoltaic panel presented the best performance.
Keyword : Sun tracking, Photovoltaic, Gain, irradiance.

1. Introduction

The energy produced by any solar conversion system depends mainly on the solar energy collected by the considered system. However, to be able to collect the maximum of solar energy, the most usually used scheme, in flat plate solar applications, is a fixed solar collector surface oriented toward the equator and generally inclined according to the annual, seasonal or monthly optimum slope as those proposed in [1-15]. The flat plate solar collectors, depending on the sky state, absorb a maximum of global solar irradiance especially around midday, where the solar beam radiation takes its maximum values. Another solution has been proposed by several scientists to increase the flat plate solar system performances consisting of using sun tracker systems. This solution is exclusively applied to the solar concentrating systems which mainly use the solar beam radiation in the case where the extra costs of the mechanical system and optical elements are significantly compensated by the increase of system performance. The use of sun tracking systems in flat plate solar systems applications enables the collector's surface to constantly track the sun, hence to collect the maximum of global solar irradiance all day long. However, these systems can be economically profitable only if the extra cost related to the sun tracking mechanism is lower than the cost of the additional panels which will lead to the same power production with a system having a fixed structure. On the other hand, much research work [5-29] has been accomplished in view of demonstrating the potential benefits from using a sun tracking system in solar energy flat plate conversion applications.
In this study, five configurations of sun tracking systems, two axes, one axis vertical and one axis inclined have

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been considered. For each of the two considered one rotating axis systems, a seasonal and a yearly optimum slope have been used while, as traditional PV systems, two fixed systems have been considered and inclined respectively according to a yearly and seasonal optimum slope.

The use of sun tracker mechanisms to increase the flat plate photovoltaic systems performance for different sky state conditions has been improved at a first stage of this work. Thus, fourteen completely clear, twelve partially clear and five cloudy days representing each of the seasons of the year have been considered. The corresponding systems evaluation was performed on the basis of five minutes measured data obtained at Ghardaïa location, situated in the North of Algeria desert considered as arid, hot and dry climate. This has been achieved by quantifying separately, for each of the considered sky states, the effective global solar radiation input as well as the electrical energy output by each of the considered systems. Then, the electrical energy gain obtained by the PV panels fixed on different sun tracker systems has been calculated and compared to those obtained by the traditional fixed panels. In addition, the gain obtained by panels fixed on a dual sun tracking system and that related to those mounted on the single axis sun tracking systems have also been calculated and compared. Finally, the parameters responsible for the produced electrical energy by the considered systems as well as for the gains changes have been identified.

2. The used systems

The different systems retained in this work are summarized and listed below:

- A fixed panel system, oriented towards the equator and inclined according to the annual optimum slope (**FY**);
- A fixed panel system, oriented towards the equator and inclined according to the seasonal optimum slope (**FS**);
- A panel equipped with a single axis sun tracking system with vertical rotating axis and inclined according to respectively the annual optimum slope (**OVY**) and to the seasonal optimum slope (O**VS**).
- A panel equipped with a single axis sun tracking system with surface parallel to the rotating axis and inclined according to the annual optimum slope (**OIY)** and to the seasonal optimum slope (**OIS**);
- Two-axis sun tracking system (**DT**)

Furthermore, to calculate the amount of direct, diffuse and reflected solar irradiations collected by each of the considered systems, three main parameters are needed:

- The solar beam incidence angle θ_i ,
- The instantaneous slope of the panel surface β;
- The panel azimuth γ.

Thus, for a fixed panel surface, oriented towards the equator ($\gamma=0$) and inclined according to the slope β, the expression of the incidence angle θ_i, is given by Duffie et al [31].

In this work, two optimum panel surface slopes have been used, the annual and the seasonal optimum slope. The retained model to calculate the annual optimum slope is that proposed by Gladius [1] and to calculate the seasonal optimum slope that proposed in the work of Elminir et al [32] has been used.

The equations proposed by Braun et al. [33] are used for calculating the needed angles to evaluate the solar irradiance components incident on panel mounted on a single vertical and inclined rotating axis as well as that fixed on the two-axis sun tracking system.

3. The used Photovoltaic model

To compare and improve the different sun tracker systems effect on the solar flat plate systems performance, a theoretical photovoltaic model has been used.

Several photovoltaic models have been proposed by scientists [34-39] describing the cell, module or panel behavior and operation. These models are different by the process from calculation, the precision and the number of parameters intervening in the Current – Voltage characteristic. The one proposed by Towsend [38] based on four parameters, has been employed in this study for which the equivalent electrical circuit is given in Fig.1 and the corresponding current – voltage relationship is given by Eq. (1)

$$I = I_L - I_0\left[\exp\left(\frac{q}{\gamma_p k T_c}\right)(V + IR_s) - 1\right] \tag{1}$$

where q, is the electron charge 1.602 10^{-19} C, k, Boltzmann's constant, 1.381 10^{-23} J/°K , T_c is the temperature of the solar cell which is function of global solar irradiance and ambient air temperature, I and V are respectively the operating current (A) and voltage (V) of the module, I_L is the photocurrent (A) which depends linearly on the incident solar radiation and I_0 is the diode reverse saturation current (A) which is function of solar cell temperature. γ_p and R_s are respectively, the empirical photovoltaic curve fitting parameter and the module series resistance (Ohms).

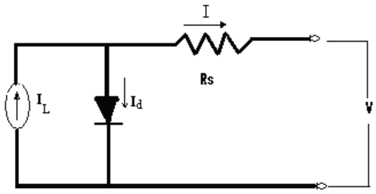

Fig. 1 Electrical equivalent circuit of the four parameters PV cell model

The output power from one photovoltaic cell is very small. To produce the required power for supplying any load, many cells are to be connected in series and parallel to build a module. Modules are also combined into panels. These panels are connected together to build the entire photovoltaic array. However, to describe the I-V characteristic for the considered array, the previous calculated parameters are needed and can be scaled in the following way:

- The total panel photo-current:

$$I_{L,tot} = NP\ I_L \tag{2}$$

- The total panel diode reverses current:

$$I_{0,tot} = NP\ I_0 \tag{3}$$

- The empirical PV curve fitting parameter:

$$\gamma_{tot} = NS\gamma_p \tag{4}$$

- The total panel series resistance

$$R_{s,tot} = \frac{NS}{NP} R_s \tag{5}$$

If panels are connected in series the output voltage increases but if they are connected in parallel the output current increases, according to the following equations:

$$I_{tot} = NP\ I \tag{6}$$

$$V_{tot} = NS\ V \tag{7}$$

Where *NS* and *NP* are, respectively, the number of modules connected in parallel and in series.

In this study, a BP 380 photovoltaic module, whose characteristics are obtained from [40], has been used for evaluating the electrical energy output of different sun tracking mechanisms.

4. Calculation of the hourly effective global solar irradiance on an inclined surface.

For a real case and for all photovoltaic system studies, two main characteristics of the considered plant are required: the surrounding air temperature T_a and global solar irradiance $G(\beta,\gamma)$ incident on the photovoltaic panel. So, in this study, to consider the effect of the incidence angle modifier on the amount of solar irradiance transmitted, absorbed and converted to electricity by cells, the effective global solar irradiance is considered which is calculated by Eq. (8):

$$G_{eff}(\beta,\gamma) = B(\beta,\gamma)K_{\tau\alpha} + D(\beta,\gamma)K_{\tau\alpha,d} + R(\beta,\gamma)K_{\tau\alpha,r} \tag{8}$$

where $B(\beta,\gamma)$, $D(\beta,\gamma)$ and $R(\beta,\gamma)$ are, respectively, the direct, diffuse and reflected solar irradiance components incident on the considered panel.

$K_{\tau\alpha}$, $K_{\tau\alpha,d}$ and $K_{\tau\alpha,r}$ are respectively the incidence angle modifiers for direct, diffuse and reflected solar irradiances.

4.1 Direct solar irradiance calculation

The direct solar irradiance incident on a plan with any orientation and slope is calculated by Eq.(9)

$$B(\beta,\gamma) = Bn\cos(\theta_i) \qquad (9)$$

where B_n and θ_i are respectively the normal direct solar irradiance and it's incidence angle on the panel surface.

4.2 Diffuse and ground reflected solar irradiance calculation

In this work, the distribution of the diffuse solar radiation is assumed anisotropic and the model proposed by Klucher [42] and modified by Baltas et al. [44] has been used. On the other hand, the solar irradiance reflected by the ground is quantified by using the model proposed in [43] and presented in [41] in which the distribution of the solar irradiance reflected by the ground surface is also assumed as anisotropic.

4.3 The incidence angle modifier

The incidence angle has been defined by Duffie et al [31] as follows:

$$K_{\tau\alpha}(\theta_i) = \frac{\tau(\theta_i)}{\tau(0)} \qquad (10)$$

where $\tau(0)$ and $\tau(\theta_i)$ are respectively the cover transmittance at normal incidence and at an incidence angle equal to θ_i. King et al. [46] provide a cell specific equation for the incidence angle modifier under correlation form, expressed by Eq.(11):

$$K_{\tau\alpha}(\theta_i) = \sum_{1}^{5}\left(a_i\theta_i\right) \qquad (11)$$

The polynomial coefficients a_i have been determined by Fanny et al [47] for several cell types and presented by De Soto et al [48]. The incidence angle modifier $K_{\tau\alpha}$ takes this effect in consideration and corrects the irradiation components in the effective irradiation equation. So, the $K_{\tau\alpha,d}$ and $K_{\tau\alpha,r}$ respectively incidence modifier angles for diffuse and reflected solar irradiance are calculated at an incidence angle equal to 58 degrees.

5. The used data

In this work, over the different seasons of the year and from a set of four years of data measurement (2004-2007), fourteen clear days, twelve partially clear days characterized by different clarity level factors and five cloudy days have been selected and the corresponding five-minute step time of direct normal, horizontal global and diffuse solar irradiances as well as air temperature data measurements used as input. These have been collected at Ghardaïa site, located in the north of Algeria's desert (latitude =32.4°N, longitude 3.8° E and altitude=468 meters).

According to the Koppen Geiger climates classification presented in Peel et al [49], the climate of this site is classified as an arid hot and dry climate (Gwh). It should be noted that Kipp and Zonen [50] CM11 precision Pyranometer has been employed for measuring the global solar irradiance. This type of Pyranometer, equipped with shadow ring, has been used to measure the diffuse solar irradiance. The shadow ring has been installed according to Kipp and Zonen [50] instructions which state that its axis must always be parallel to the polar axis. Because the shadow band screens the sensor from a portion of the incident diffuse solar radiation coming from the sky, a correction has been applied to the measurements following the coefficient proposed by Batlles et al [51]. The solar beam has been measured by using an Eppley Pyrheliometer equipped with an equatorial sun tracking mechanism and the instantaneous temperature is measured by the Jules and Richard thermo hygrograph recorder. In Table 2 are presented the measured parameters, the corresponding measuring instruments and accuracies of the sensors supplied by the manufacturers. The verification of the accuracy of the instruments is continuously updated on the basis of the comparison of the measured and calculated global solar irradiance by Eq. (12):

$$G_h = B_n\sin(h) + D_h \qquad (12)$$

where B_n, D_h and h are respectively the normal direct, horizontal diffuse solar irradiance and solar altitude. The difference between the calculated and measured global solar irradiance amounts has been analyzed. Then using the supplied data by the manufacturer (see Table 1), as indicated above and the propagation error technique, presented by Glesner [52], the global solar irradiance error has been estimated to be +-6%, which is usually admitted as the acceptable limit of accuracy of measurement. It should also be noted that all solar irradiance sensors are connected to an automatic data acquisition system, the Data logger LI-1000 which provides good reliability with a high accuracy and a five minutes recording time step is used. In order to avoid any erroneous data, the calibration of the meteorological instruments and solar sensors is regularly checked.

Table 1 Equipments used for measuring solar irradiance and dry air temperature

Parameter measurement	Unit	Type of Sensor	Accuracy
Horizontal global solar irradiance	W/m²	Pyranometer Kipp and Zonen CM11	±2%
Horizontal diffuse solar irradiance	W/m²	Pyranometer Kipp and Zonen CM11 mounted under a shading ring	±2%
Direct normal solar irradiance	W/m²	1.1. Eppley pyrheliometer, mounted on an equatorial sun tracher	±2%
Dry air température	W/m²	1.2. Jules Richard and Peckley Thermo-hygrograph	±3%

6. Results and discussion

In view of knowing the received amount of solar energy, the corresponding electrical energy produced by the different considered systems under different sky conditions, how the use of sun tracking systems affects the photovoltaic systems performances and which among the parameters are responsible for the obtained gains, each of the considered sky state conditions is studied and presented separately. Additionally, in this study, the yearly optimum slope is needed. This is calculated by using the model proposed by Gladius [1] into which the monthly mean daily horizontal global solar irradiation data, recorded over a four-year period (2004-2007) at the Renewable Energy Development Center at Ghardaïa site is used as input. As results, the estimated yearly optimum slope β_y is equal to 39.4 degrees.

6.1 Clear sky state

In this work, a clear sky day is defined as a day on which there is no cloud passing from sunrise till sunset. A Matlab program has been developed which, having as inputs the measured direct normal, horizontal global and diffuse solar irradiance as well as the ambient air temperature related to the retained completely clear days, BP380 module characteristics, location latitude and time and, using theoretical parameters and models mentioned in sections 2 and 4, the corresponding effective solar irradiance has also been calculated and, according to Towsend [38] model, the program also calculates the five-minute step time power-voltage characteristics of the considered panel (six parallel series connected pairs of modules). The corresponding Power P_{mp} and Voltage V_{mp} output at the maximum power point conditions have been calculated. From these latter characteristics, the obtained *Pmp* is considered as the output power of the PV panel and, on this basis, the hourly and daily electrical energy is calculated.

From results presented in Table 2, it is noticed that the daily amount of the produced electrical energy depends on the considered sun tracking system, the optimum angle at which the panel is fixed and the vertical or inclined rotating axes are tilted, the considered day representing the season characterized by the theoretical day length D_L as well as the daily clarity level indicators. To highlight the effect of these parameters on the PV system performances, each of the considered cases is disused separately

6.1.1 Effect of sun tracking systems

The results presented in Table 2 show that all PV panels mounted on the sun tracking systems (**OVY, OVS, OIY, OIS** and **DT**) produced more electrical energy than those mounted on fixed structures, **FY** and **FS.**

Furthermore, the highest gains obtained are those related to the two-axis sun tracking systems, followed gradually by the inclined and then by the vertical rotating axis systems for the same optimum tilt angle. This is also valid for the seasonal and yearly optimum slope for the same rotating axis. The PV panel mounted on the **DT** system presented a relatively smaller additional electrical energy gain to that obtained by the PV panels fixed on the single axis sun tracking systems (**OVY, OVS, OIY** and **OIS**). This is explained by the fact that during the day, the panel equipped with the **DT** tracking mechanisms is continuously oriented towards the sun, making the surface receive the solar beam with a zero incidence angle value which is not the case for single-axis sun tracking systems neither for the traditional fixed panels. This is more noticeable around midday solar time (see Fig. 2) during which the single-axis sun tracking systems **OVY, OVS** and **OIY, OIS** take, respectively, the same orientation and inclination as the **FY** and **FS** systems and thus receive and produce the same amount of global solar irradiance and electrical power.

From the above, the range of the obtained gains is in good agreement with figures presented in published work. The obtained results are further confirmed by other research works related to the multi-axis sun tracking systems. Indeed, for the dual axis sun tracking systems and a single vertical rotating axis, the calculated electrical power gain evaluates to 45-65%, 36-38% (1st of May) as compared to the two fixed panel systems while up to 43.87%, 37.53% and 34.43% for two-axis, East-West and vertical tracking systems (19th of May), respectively, with the panel surface inclined at the latitude of the location and oriented toward the equator, are reported [27] for instance.

6.1.2 *Effect of day length*

From Table 2, the results show that for two days representative of two different seasons, having respectively the nearly equal values of K_T and K_D and having a different day length, the amount of electrical energy and sun tracking systems gain are proportional to the length of the considered day.

This is confirmed by the results related to the 3rd (D_L=9.90 hours) and the 6th (D_L= 9.93 hours) of January, the 1st of April (D_L=12.35 hours), the 1st of May (D_L=13.32 hours) and the 30th of September 2004 (D_L=11.67 hours). These five days present nearly equal values of K_T and K_D and different days lengths, the amount of produced electrical energy obtained by different systems and the corresponding sun tracking systems gain takes higher values for the :

Table 2. Cumulative daily electrical energy produced by the different systems and daily gain produced by the moved panels to that produced by the fixed panel (clear sky state case).

		FY	OVY	OIY	DT	FS	OVS	OIS	DT	K_T	K_D	D_L
3rd of	**Sum [kWh/day]**	6.885	7.954	8.217	8.815	7.144	8.426	8.530	8.815	**0.76**	**0.13**	**9.90**
Jan	**Ad1[%]**		**15.52**	**19.34**	**28.04**		**17.95**	**19.41**	**23.34**			
2005	**Ad2[%]**		**10.83**	**7.29**			**4.61**	**3.34**				
6th of	**Sum [kWh/day]**	7.169	8.374	8.665	9.340	7.459	8.919	9.032	9.340	**0.79**	**0.10**	**9.93**
Jan	**Ad1[%]**		**16.82**	**20.87**	**30.28**		**19.57**	**21.09**	**25.22**			
2005	**Ad2[%]**		**11.52**	**7.78**			**4.72**	**3.41**				
27th	**Sum [kWh/day]**	7.381	8.187	8.475	9.014	7.556	8.660	8.789	9.014	**0.74**	**0.36**	**12.17**
Mar	**Ad1[%]**		**10.93**	**14.84**	**22.13**		**14.63**	**16.33**	**19.31**			
2007	**Ad2[%]**		**10.10**	**6.35**			**4.08**	**2.56**				
1st of	**Sum [kWh/day]**	7.494	8.975	9.158	10.823	7.599	10.528	10.563	10.823	**0.78**	**0.13**	**12.35**
Apr	**Ad1[%]**		**19.77**	**22.21**	**44.43**		**38.55**	**39.01**	**42.43**			
2006	**Ad2[%]**		**20.59**	**18.18**			**2.80**	**2.46**				
1st of	**Sum [kWh/day]**	7.395	10.266	11.439	12.209	8.416	11.461	11.999	12.209	**0.79**	**0.12**	**13.32**
May	**Ad1[%]**		**38.82**	**54.68**	**65.09**		**36.18**	**42.58**	**45.07**			
2005	**Ad2[%]**		**18.93**	**6.73**			**6.53**	**1.75**				
9th of	**Sum [kWh/day]**	6.021	8.318	8.617	9.484	7.332	8.948	9.126	9.484	**0.74**	**0.32**	**14.11**
June	**Ad1[%]**	**38.14**	**43.11**	**57.50**	**22.04**	**24.46**	**29.34**					
2006	**Ad2[%]**	**14.02**	**10.05**		**5.99**	**3.92**						
30th	**Sum [kWh/day]**	6.201	8.657	9.327	9.903	7.593	8.970	9.527	9.903	**0.75**	**0.28**	**14.14**
June	**Ad1[%]**		**39.61**	**50.40**	**59.70**		**18.14**	**25.48**	**30.43**			
2004	**Ad2[%]**		**14.39**	**6.19**			**10.40**	**3.95**				
1st of	**Sum [kWh/day]**	6.199	7.782	8.281	8.921	7.207	8.442	8.579	8.921	**0.72**	**0.33**	**14.14**
July	**Ad1[%]**		**25.55**	**33.59**	**43.92**		**17.14**	**19.04**	**23.79**			
2007	**Ad2[%]**		**14.63**	**7.73**			**5.67**	**3.99**				
5th of	**Sum [kWh/day]**	6.002	8.007	8.642	9.152	7.267	8.417	8.809	9.152	**0.73**	**0.34**	**14.10**
July	**Ad1[%]**		**33.39**	**43.98**	**52.47**		**15.82**	**21.20**	**25.92**			
2004	**Ad2[%]**		**14.30**	**5.90**			**8.72**	**3.90**				
6th of	**Sum [kWh/day]**	6.048	7.685	7.978	8.654	6.575	8.215	8.456	8.654	**0.71**	**0.35**	**13.47**
Aug	**Ad1[%]**		**27.07**	**31.91**	**43.09**		**24.94**	**28.61**	**31.62**			
2005	**Ad2[%]**		**12.61**	**8.48**			**5.34**	**2.31**				
19th of	**Sum [kWh/day]**	6.427	8.070	8.477	9.032	7.078	8.641	8.877	9.032	**0.74**	**0.33**	**13.09**
Aug	**Ad1[%]**		**25.55**	**31.89**	**40.52**		**22.08**	**25.42**	**27.61**			
2004	**Ad2[%]**		**11.92**	**6.54**			**4.50**	**1.74**				
17th of	**Sum [kWh/day]**	6.780	8.067	8.182	8.473	6.822	8.255	8.388	8.473	**0.75**	**0.26**	**11.10**
Oct	**Ad1[%]**		**18.64**	**20.33**	**24.61**		**21.01**	**22.97**	24.97			
2005	**Ad2[%]**		**5.03**	**3.55**			**2.65**	**1.01**				
30th of	**Sum [kWh/day]**	6.567	8.213	8.296	8.619	6.618	8.310	8.475	8.619	**0.75**	**0.21**	**11.67**
Sep	**Ad1[%]**		**24.10**	**25.36**	**30.23**		**24.21**	**29.07**	**31.25**			
2005	**Ad2[%]**		**4.94**	**3.88**			**3.71**	**1.69**				
30th of	**Sum [kWh/day]**	7.507	9.932	10.383	10.594	7.556	10.093	10.446	10.594	**0.78**	**0.16**	**11.67**
Sep	**Ad1[%]**		**38.30**	**38.32**	**41.12**		**33.57**	**38.24**	**40.20**			
2004	**Ad2[%]**		**6.66**	**2.04**			**4.96**	**1.41**				

- 1st of May and succeeded respectively by those of the 1st of April, 30th of September and by those relative to the 6th and 3rd of January;

- Again, this is confirmed also by:
  - o Comparing the results related to the 27th of March (D_L=12.17 hours) and those obtained during the 9th of June (D_L= 14.11 hours);
  - o Comparing the results related respectively to the 30th of June, the 30th of September 2005 and those of the 17th of October;

6.1.3 Effect of optimum slope

o Once more the results presented in Table 2, also show that the fixed PV panels **FY** and **FS** production is linked to the season and to the corresponding tilde angle at which is inclined each one of the considered systems and **FS** system produced more electrical energy than the **FY** system. So, during the day on which the solar declination is lower or close to zero value, small additional amounts of electrical energy are produced by the **FS** system to that obtained by the **FY** system but these amounts are more significant in the case of the days characterized by positive values of the sun declination.

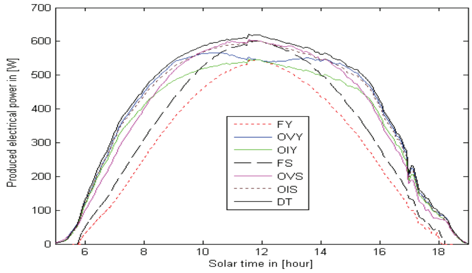

Fig. 2 Produced electrical power by different systems during the 1st of July 2007 considered as a clear day

Once again, from results presented in Table 2, it is observed that the daily amounts of produced electrical energy and the obtained gains also depend mainly on the sky clarity level of the considered day. Furthermore, additionally to the previous results, this case will be discussed in the following subsection.

6.2 Partially clear days

During the year, mainly in winter season, some days are characterized by clear sky periods frequently alternating with cloudy ones. Consequently, the quantity of incidental global solar irradiance on any surface strongly depends on the cloud type and its passing frequency.
In the solar application field and for a considered period, the sky state is characterized by its corresponding clearness index K_T. To observe the daily clarity level effect on the sun tracking systems gain, eleven days among the measured data have been selected, for which the relations $0.26 \leq K_T \leq 0.68$ and $0.37 \leq K_D \leq 0.98$ holds.
The collected five-minutes step time global solar irradiance, current-voltage, power-voltage characteristics, the PV panel power P_{mp} output at the maximum power point conditions, the daily cumulative effective global solar irradiation collected and the corresponding produced electrical energy by the different systems have been calculated by using the same MATLAB program and in the same manner than that used in the case of daily clear sky states. However, the obtained values of S_{um}, Ad, K_T, K_D and D_L related to each of the considered systems and to each of the eleven retained partially clear days are presented in Table 3. The obtained results confirm and also show that as experienced in the case of clear day's results, the daily electrical energy amounts produced by each of the various schemes and the corresponding electrical gains depend on the employed sun tracking system, the day length and the used optimum slope.
Even though the sky clarity level indicators for the 20th of January (see Table 3) showed that during this day, cloud cover was less present than during the 15th of April, the 3rd of June, the 12th of June and the 9th of September but the amount of daily cumulative electrical energy produced by each of the considered systems and the corresponding gain remained lower. This is the case, if the results related to the 8th of April are considered and compared with those obtained during the 8th of October and also if a comparison between the results obtained during the 15th of March, the 2nd of June and the 21st of December was made.
In addition, from the presented results, it appears that the dependence of the amount of daily produced electrical energy by the different systems and the corresponding gains is also significant from the daily sky clarity level. Thus, during the 9th of September, the 2nd of June and the 21st of December, the different PV systems produced nearly the same amounts of electrical energy but those produced during the 3rd and 12th of June are more important and differ from one system to another.
This can be explained by the fact that lower and higher values of K_T and K_D, related respectively to September 9th, June 2nd and December 21st (see Table 3), explain that during these days, the clouds passing frequency was

important which lead the different systems to collect a small amount of direct solar irradiance on which strongly depend the PV systems performances.

Contrariwise, according to K_T and K_D values representing the sky states of the 3rd and 12th of June, the clouds passing frequency during these days is lower. Consequently, direct solar irradiance is available for longer periods of time and, according to the considered PV panel, higher amounts of electrical energy are produced. On an other hand, considering the results related to the clear sky days presented in Table 2 together with the results presented in Table 3, it becomes more apparent that for close day length values, the amounts of electrical energy produced by different PV panel systems and the amounts of sun tracking systems gains depend on the daily clarity level factors. Thus, if the results related to January 3rd (see Table 2) are compared to those obtained for December 21st (see Table 3), the obtained gains in the first case are much greater than those obtained in the second one.

The same observation can be made if :

- The results related to March 27th (see Table 2) are considered and compared to those of March 15th (see Table 2).
- The 1st of April results (see Table 2) and those of the 8th and 15th of April (see Table 3) are considered;
- If those of the 9th and 30th of June (see Table 2) are considered and compared to those of the 2nd, 3rd and 12th of the same month presented in Table 3.
- This means that the amount of electrical energy produced by a PV system and the sun tracker systems gains are mainly linked to the length and the representative clarity level factors of the considered day. Additionally, compared to the previous work, the obtained results are in good agreement with those reported in [22]. Indeed, the gain obtained by any sun tracker system strongly depends on the sky state characterized by the clearness index which is linked to the amount of direct solar irradiance.

Table 3 Cumulative daily electrical energy produced by the different systems and daily gain produced by the moved panels to that produced by the fixed panel (Partially clear sky state case)

		FY	OVY	OIY	DT	FS	OVS	OIS	DT	KT	KD	DL
20th	**S_{um} [kWh/day]**	4.450	4.756	4.768	4.832	4.472	4.781	4.791	4.832	**0.63**	**0.54**	**10.16**
Of	**Ad1[%]**		**6.89**	**7.15**	**8.60**		**6.91**	**7.13**	**8.06**			
Jan	**Ad2[%]**		**1.59**	**1.35**			**1.08**	**0.86**				
15th	**S_{um} [kWh/day]**	3.651	3.752	3.806	3.938	3.715	3.809	3.868	3.938	**0.48**	**0.90**	**11.76**
Of	**Ad1[%]**		**2.75**	**4.24**	**7.84**		**2.51**	**4.11**	**5.99**			
Mar	**Ad2[%]**		**4.96**	**3.46**			**3.39**	**1.80**				
8th	**S_{um}[kWh/day]**	6.613	7.480	7.484	7.914	6.989	7.691	7.740	7.914	**0.68**	**0.47**	**12.58**
Of	**Ad1[{%]**		**13.10**	**13.16**	**19.67**		**10.03**	**10.73**	**13.23**			
Apr	**Ad2[%]**		**5.81**	**5.76**			**2.90**	**2.26**				
15th	**S_{um}[kWh/day]**	4.769	5.057	5.163	5.357	5.001	5.126	5.228	5.357	**0.55**	**0.75**	**12.82**
Of	**Ad1[%]**		**6.04**	**8.27**	**12.33**		**2.50**	**4.53**	**7.11**			
Apr	**Ad2[%]**		**5.93**	**3.74**			**4.49**	**2.47**				
2nd	**S_{um} [kWh/day]**	3.855	3.989	4.057	4.293	4.008	4.066	4.109	4.293	**0.43**	**0.91**	**14.02**
Of	**Ad1[%]**		**3.48**	**5.24**	**11.38**		**1.44**	**2.52**	**7.12**			
June	**Ad2[%]**		**7.64**	**5.83**			**5.60**	**4.49**				
3rd	**S_{um}[kWh/day]**	4.677	4.980	5.126	5.554	4.788	5.174	5.286	5.554	**0.56**	**0.83**	**14.07**
Of	**Ad1[%]**		**6.49**	**9.61**	**18.75**		**8.05**	**10.39**	**15.98**			
June	**Ad2[%]**		**11.52**	**8.34**			**7.34**	**5.06**				
12th	**S_{um} [kWh/day]**	5.117	5.508	6.052	6.387	5.487	6.094	6.**284**	**6.387**	**0.59**	**0.67**	**14.13**
Of	**Ad1[%]**		**7.64**	**18.27**	**24.83**		**11.07**	**14.53**	**16.41**			
Jun e	**Ad2[%]**		**15.97**	**5.54**			**4.81**	**1.64**				
9th	**S_{um} [kWh/day]**	3.792	4.211	4.529	4.844	4.136	4.527	4.658	4.844	**0.50**	**0.75**	**12.43**
Of	**Ad1[%]**		**11.04**	**19.43**	**27.73**		**9.47**	**12.63**	**17.12**			
Sep	**Ad2 [%]**		**15.02**	**6.95**			**6.99**	**3.99**				
25th	**S_{um} [kWh/day]**	6.094	6.148	6.238	6.322	6.088	6.170	6.278	6.322	**0.59**	**0.40**	**11.88**
Of	**Ad1[%]**		**0.88**	**2.35**	**3.73**		**1.35**	**3.12**	**3.84**			
Sep	**Ad2[%]**		**2.83**	**1.35**			**2.46**	**0.70**				
8th	**S_{um} [kWh/day]**	5.560	6.077	6.160	6.251	5.607	6.153	6.177	6.251	**0.67**	**0.40**	**11.43**
Of	**Ad1[%]**		**9.30**	**10.81**	**12.43**		**9.74**	**10.17**	**11.48**			
Oct	**Ad2[%]**		**2.86**	**1.47**			**1.59**	**1.20**				
21st	**S_{um} [kWh/day]**	2.198	2.358	2.372	2.410	2.225	2.377	2.396	2.410	**0.41**	**0.88**	**9.84**
Of	**Ad1[%]**		**7.30**	**7.95**	**9.65**		**6.83**	**7.68**	**8.32**			
Dec	**Ad2[%]**		**2.19**	**1.58**			**1.39**	**0.60**				

6.4 Cloudy Days

In this study, a cloudy day is defined as a day for which the daily cumulative amount of the collected normal direct solar irradiance is very small or equal to zero. However, it is well known that solar applications are most interesting if the state of the sky is clear. But once installed, in any location, the photovoltaic panel should work under different sky states and under different weather conditions. In this work, the behavior of the retained systems during cloudy sky days over the different seasons of the year has been regarded as very interesting and considered. To this end, January the 27th, 2005 (the cumulative daily normal direct solar irradiation is equal to zero), May the 25th, 2006, August the 6th, 2004 and October the 11th 2004 (a small amounts of normal direct solar irradiation was collected), representing respectively winter, spring, summer and fall seasons have been selected.

In addition to the previous cases of sky state results, In Table 4, is presented the cumulative daily electrical energy produced by the same panels installed on a horizontal surface $\boldsymbol{P_h}$.

From results presented in Table 4, the following can also be noted:

- *Ad* values, the daily amount of additional electrical energy produced by the PV panels mounted on the different sun tracking systems remains very small during, May the 25th, August the 6th, 2004, the 10th, 2007 and October the 11th, 2004;
- The negative values of *Ad* relative to the 27th of January mean that the amount of electrical energy produced by the fixed panels **FY** and **FS** is greater or equal to that produced by moved panels.

This confirms that sun tracking systems effect on the PV system performances depends mainly on the sky clarity level and also means that in the case of cloudy sky state, tracking the sun for increasing the PV system performance is not necessary. Otherwise, the obtained results can be explained by the fact that during the cloudy days, especially during those characterized by a total absence of direct solar irradiance, only that diffused by the atmosphere and that reflected by the ground dominate. The distribution of the diffuse solar irradiance has been considered as anisotropic and the use of the view model proposed by Baltas et al. [44] reduced to the isotropic model in which the expression $(1+ \cos(\beta))/2$ is considered as the form factor. On the other hand the reflected solar radiation by the ground is also assumed to be isotropic and, $(1-\cos(\beta))/2$ is the corresponding form factor. Consequently, the collected amount of solar irradiance and the electrical power produced by the considered PV panels do not depend on the panel surface azimuth but depend strongly on its inclination according to the slope of the panels. However, the two form factors are generally lower than unity for an inclined surface and become equal to it for a horizontal surface. This position leads the PV panel to receive the totality of the diffuse solar irradiance. This can be confirmed from $\boldsymbol{P_h}$ values, the daily electrical energy produced when the same panel is installed on a horizontal surface which is presented in the last column of Table 5. It appears from this table that the amount of electricity produced by horizontal panels is much higher than that produced by the considered fixed or moved surfaces, which is confirmed by [53].

Table 4 Cumulative daily electrical energy produced by the different systems and daily gain produced by the moved panels to that produced by the fixed panel (Cloudy sky state case).

		FY	OVY	OIY	DT	FS	OVS	OIS	DT	P_h	K_T	K_D	D_L
27th of Jan	**S_{um}[kWh/day]**	1.430	1.422	1.373	1.336	1.385	1.388	1.338	1.336	1.651	**0.21**	**0.98**	**10.31**
	Ad1[%]		**-0.57**	**-3.43**	**-6.05**		**0.19**	**-3.44**	**-3.55**				
25th of May	**S_{um} [kWh/day]**	3.612	3.637	3.673	3.845	3.802	3.816	3.820	3.845	4.155	**0.32**	**0.91**	**13.87**
	Ad1[%]		**0.71**	**1.69**	**6.47**		**0.34**	**0.45**	**1.13**				
6th Of Aug	**S_{um}[kWh/day]**	2.010	2.011	2.017	2.065	2.059	2.061	2.062	2.065	2.141	**0.27**	**0.92**	**13.45**
	Ad1[%]		**0.07**	**0.38**	**2.76**		**0.07**	**0.02**	**0.03**				
10th Of Aug	**S_{um} [kWh/day]**	2.111	2.158	2.174	2.201	2.168	2.181	2.188	2.201	2.633	**0.26**	**0.90**	**13.34**
	Ad1[%]		**2.23**	**2.96**	**4.25**		**0.59**	**0.90**	**1.51**				
11th Of Oct	**S_{um} [kWh/day]**	1.791	1.806	1.830	1.860	1.793	1.819	1.836	1.859	1.994	**0.27**	**0.96**	**11.31**
	Ad1[%]		**0.79**	**2.14**	**5.80**		**1.40**	**2.36**	**3.6**				

7. Conclusion

In this work, the performance of PV panels mounted on fixed structures inclined according to a yearly and seasonal optimum slope, panels fixed onto single axis sun tracking system with vertical and inclined rotating axis, for which a yearly and seasonal optimum slopes have also been used, as well as of those mounted on two-axis sun tracker mechanisms have been considered and analyzed employing data collected over thirty one selected days. These data represent the different PV panel operating conditions.

The electrical energy produced by the different considered systems as well as the gains have been evaluated and the obtained results allowed establishing the following: The employment of sun tracker mechanisms contributes considerably to increasing the photovoltaic systems performance;

- The use of sun tracker mechanisms in solar flat plate applications is very beneficial during clear sky days, unnecessary during cloudy sky days and depends mainly on the considered season and daily clarity level for partially clear days;
- During clear days, the highest amount of additional electrical energy produced by the different moved panels to that obtained by the fixed traditional PV panels is obtained during the period covering the morning and afternoon;
- For a completely cloudy day, the results show that all considered systems produced closely the same amount of electrical energy and the horizontal position of the panel presented the best performance compared to those of the inclined panel's positions, one-axis and two-axis sun tracking systems;
- The additional amount of electrical energy produced by a moved PV panel compared with the fixed panels depend mainly on the employed sun tracker system, the sky clarity level of the considered day and on the seasonal evolution of the day length;
- Using the two-axis sun tracker system enables the PV panel produce higher amounts of electrical energy which decrease gradually from the single inclined to vertical rotating axis sun tracker systems if the

same optimum slope is considered and from the seasonal to the yearly optimum slopes if the same single rotating axis is considered;

- Other parameters such as dust and water deposits on the surface affect the PV panel performance. In order to confirm the presented simulation results, experimental work taking into account such parameters is being carried out. The related results will be reported in the future.

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Nomenclature

Ad	Additional electrical energy produced by the photovoltaic system (percent)
B_n	Measured normal direct solar irradiance in (W/m^2)
$B(\beta,\gamma)$	Direct solar irradiance incident on an inclined PV panel surface (W)
$D(\beta,\gamma)$	Diffuse solar irradiance incident on an inclined PV panel surface (W)
D_h	Horizontal diffuse solar irradiance (W/m²)
D_L	Theoretical Day length in (hour)
$G(\beta,\gamma)$	The global solar radiation collected by an inclined panel surface (W)
$G_{eff}(\beta,\gamma)$	Effective global solar irradiance incident on an inclined panel surface (W)
G_h	Global solar irradiance (W/m^2)

h Sun elevation (degrees)
I Module delivered current (A)
I_0 Diode reverses saturation current under real conditions (A)
I_{0tot} Total diode reverses saturation current under real conditions (A)
$I_{L,tot}$ Total panel's photocurrent under real conditions (A)
I_L Module photocurrent under real conditions (A)
$I_{L,ref}$ Module photocurrent under reference conditions (A)
I_{tot} Total current delivered by the PV panel (A)
k Boltzmann's constant =1.381 10^{-23} (J/°K)
K_D Ratio of diffuse solar irradiation to global solar irradiation
K_T Clearness index
$K_{\tau\alpha}$ Incidence angle modifier for the direct solar irradiance
$K_{\tau\alpha,d}$ Incidence angle modifier for the diffuse solar irradiance
$K_{\tau\alpha,r}$ Incidence angle modifier for the reflected solar irradiance
NP Number of parallel modules
NS Number of series modules
P_h Daily horizontal PV module electrical energy production (W)
P_{mp} PV panel electrical energy power output at maximum power point (W)
q Electron charge in 1.6 10^{-19} (Coulomb)
R_s Resistance of series module (Ohms)
S_{um} Daily electrical energy in (MJ)
Ta Ambiant air temperature (°C)
T_c Temperature of cell under real conditions (°C)
V Module output voltage (V)
V_{tot} Total output voltage of the PV panel (V)
V_{mp} Module output voltage at the maximum PV power point output (V)

Greek symbols
α Module cell's absorption coefficient
β Slope of panel (degrees)
φ Latitude (degrees)
γ_s Sun azimuth (degrees)
γ_p Empirical photovoltaic curve fitting parameter
γ_{tot} Total empirical photovoltaic curve fitting parameter
θ_i Incidence angle (degrees)
τ Module's cover transmission coefficient